CAAP Quarterly Report

Date of Report: <*January* 11th, 2018>

Contract Number: <DTPH56-15-H-CAAP06>

Prepared for: <Government Agency: U. S. DOT PHMSA >

Project Title: <*Mitigating Pipeline Corrosion Using A Smart Thermal Spraying Coating System*>

Prepared by: <North Dakota State University>

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For quarterly period ending: <*January* 10th, 2018>

Business and Activity Section

(a) Generated Commitments

No changes to the existing agreement.

No equipment purchased over this reporting period.

No supplies purchased in this quarter.

(b) Status Update of Past Quarter Activities

In this quarter, studies were mainly focused on the literature review of pipeline corrosion risk management system (Task 3.3) and the corrosion resistance of cold sprayed Al-Zn coatings (Task 2). The detail of this report include: 1) pipeline risk management system based on corrosion monitoring data; 2) design and preparation of cold sprayed Al-Zn coating; 3) electrochemical corrosion test setup for cold sprayed Al-Zn coatings; and 4) electrochemical corrosion test results for cold sprayed Al-Zn coatings. Further efforts will be focused on risk assessment planning based on the corrosion detection (Task 3.3) and preparation of full-size laboratory tests (Task 4.1). The detail progresses, which were completed in this quarter, are presented below:

1) Pipeline risk management system (literature review)

Risk management plays a vital role in both government regulators and pipeline industry as a successful risk management plan does not only serve as a long-term decision-making tool for optimized pipeline operation, but also ensure the public safety in the relatively close range of a pipeline. Most commonly, a risk management process would include several steps: reviewing inherent risk of the defined pipeline system, constructing risk model and evaluating risk model with available data, and then utilizing the risk model to conduct risk assessment and support decision making. A comprehensive risk model generally constructs its detailed risk structure with consideration of every possible type of incidents that could happen to the pipeline system. With the support from available data, it provides information useful for decision making in a timely manner.

Before 1990s, risk management concepts in engineering field were generally exercised informally and based on the experience of engineers, not on mathematical computation or any probability model, due to the complex of interaction between structure and environments, and lack of computational power. Early attempts to achieve risk management of pipelines either focused more on management or financial aspect, lacking details in engineering, or were case by case studies, lacking general applicable rules[1-4]. After 1990s, with exponentially increased in computation power and capabilities and the more advanced statistical studies, the risk management methodology in pipeline industry could be significantly developed.

By applying the basic idea of “risk equals probabilities times consequences”, multiple risk assessment and management model had been proposed [5-14]. Pate-Cornell proposed a probabilistic risk analysis framework for offshore platform in 1993 that taking human factors into consideration[5]. This model considered not only the incidents and corresponding hazardous results, but also the possible prevention methods. As a result, this model could be used in proactive risk management applications. In 1996, Muhlbauer proposed an index-based risk management model [8]. Instead of going from the probability of failure types, this model started from the reliability of basic components in a pipeline system. By taking into account the severity of failure of different components, this model had different maximum possible index points for different components, ranging from 0 to 100. Then based on the current status of the components, an index score would be assigned to that component. The higher score indicates higher probability of failure of that specific component. By simply adding all the index together, one could get an index reflecting pipeline overall operation risk. This model was very easy to use and quickly gained attention from pipeline industry, but its drawback also came from its simplicity: oversimplifying the cross-effects of different components. Diller proposed a quantitative risk model by constructing a matrix with risk frequency index and the severity of accident [9]. By considering casualties, environmental impact, and damage done to the equipment, this model differentiates three levels of accident severity. By combining the risk frequency index and severity of one specific type of accident, the risk of the accident could be decided. Nevertheless, this model failed to provide a comprehensive decision-making procedure, as it lacks the ability to consider every possible accident all together.

In 2004, with significant improvement of risk assessment in corrosion and adding leakage impact factor, Muhlbauer introduced the most widely used pipeline risk management framework in pipeline industry [15]. This framework model considered five major parts during the pipeline operation: third-party damage, corrosion, design, incorrect operation, and leak impact factor. In the first four parts, each part has a comprehensive list of events or components that may contribute to a pipeline failure incident, and the leak impact factor is served as an overall multiplier to control the risk related to a possible leakage. In this model, detailed component scoring table was provided and supported with historical data. The flowchart in Figure 1 shows the risk management model.

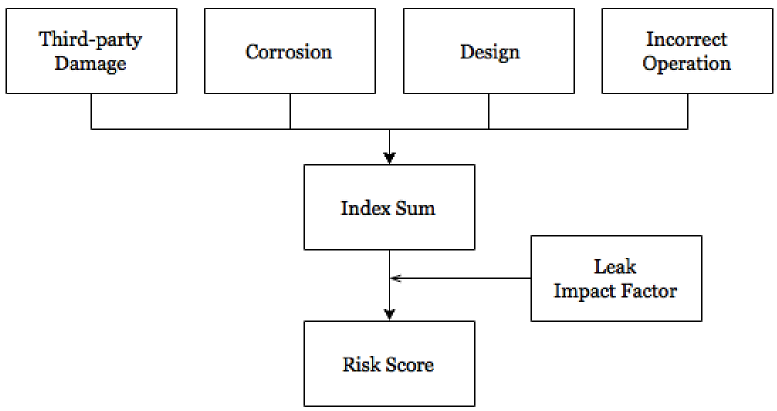

Figure 1. Risk assessment model flowchart [15].

To develop a model for risk assessment in curding components, the contributing factors include coating, environment corrosiveness, type of pipeline material, cathodic protection effectiveness, corrosiveness of the product that is transporting, etc. More recently in 2010s, with more information technology developments of big data technology, more updated risk management models have been proposed [16-24]. Most of them promised a better risk handling performance. Though they are not widely accepted as all other newly developed technologies, the ideas of using comprehensive data to dig information behind the numbers and to make objective judgement of the condition of an operating pipeline emerged. Our research goal is to integrate proposed corrosion monitoring system into this widely accepted model in industry and to make it data-driven. Detailed study would be carried out during next quarter.

2) Design and preparation of cold sprayed Al-Zn coating

To increase the flexibility in on site coating of components, it was decided to prepare coating of the optimized material (Al-Zn) as identified in previous tasks using Cold Spraying technology. Low pressure cold spray is the only deposition technique with high mobility possibilities. Cold Spraying equipment developed in Europe are relatively small and light weight with capability of being carried by single operator which can apply coating on site. If the high quality (high corrosion resistance and mechanical strength) of the cold sprayed Al-Zn is proven then it can improve flexibility of the proposed work and reduce down time of the system. Cold spraying Compared with the arc wire coating technology, cold spraying requires much less energy input and very mobile, and thus is more easily to be applied on site. Al-Zn with composition as defined in previous tasks was deposited by Plasma Giken Co, Japan, on an aluminum substrate with dimension of 1.5 in × 1.5 in × 0.5 in (3.8 cm × 3.8 cm × 1.3 cm) as shown in Figure 2 and Figure 3. The thickness of the Al-Zn deposited coating was 0.05 in (0.13 cm) as shown in Figure 4.

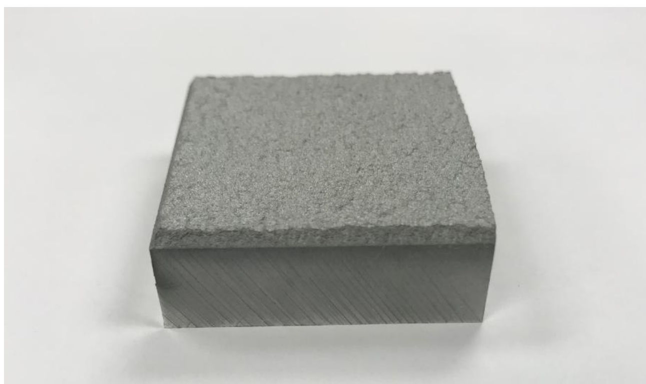
Figure 2. Sample with cold sprayed Al-Zn coating.

Figure 3. Dimensions of the sample to be tested.

Figure 4. Dimensions of the sample to be tested.

<u>3) Electrochemical corrosion test setup for samples with cold sprayed Al-Zn hard coatings</u>

It was important to compare corrosion properties of cold sprayed Al-Zn with the one deposited by wire arc spray technique. Since the size of cold sprayed sample was relatively small, a PVC pipe was attached to the sample instead of standard tubes. After using epoxy to glue PVC pipe to the surface of the coated sample, a conductive wire was attached to the bottom of the sample to connect testing instrument. Figure 5 shows the inner diameter of the PVC pipe with attached connecting wires.

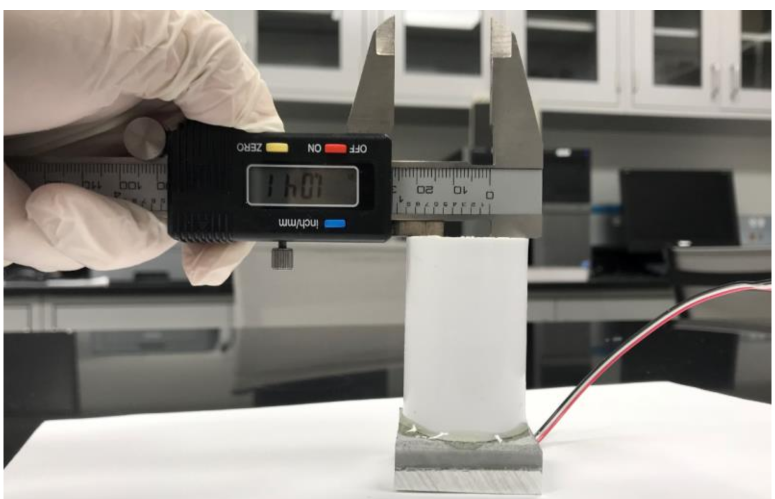
Figure 5. Inner diameter of the PVC pipe attached to sample to be tested.

Similar electrochemical corrosion test as used before was carried out by the same Gamry Reference 600 Ptentiostat/Galvanostat/ZRA on cold spray coating sample in this report. During the test, 3.5wt% NaCl solution was filled in PVC pipe as electrolyte, and the working electrode was connected to the conductive wire that was attached to the bottom of tested sample. Platinum was used as inert metal, and AgCl with KCl solution were used in reference bar. The reference bar was calibrated before electrochemical test. The electrochemical corrosion test setup is shown in Figure 6. To be consistence with previously conducted electrochemical corrosion tests, similar Tafel test was conducted on the sample.

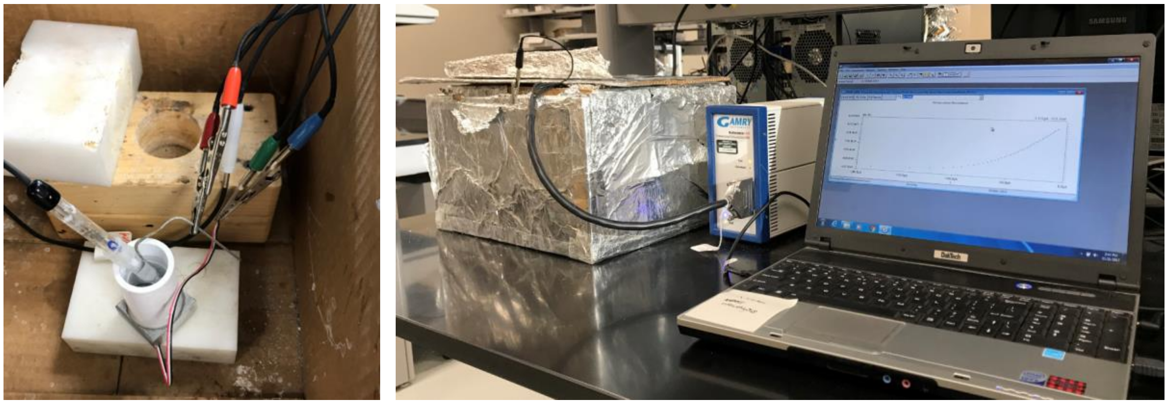

Figure 6. Electrochemical corrosion test by Gamry Reference 600.

4) Electrochemical corrosion test results for cold sprayed Al-Zn coatings

Figure 7 shows the electrochemical corrosion test result (Tafel curve). Tafel curve was a curve connected by a series of data points which represent the current measured in the testing system (y-axis, in logarithmic scale) when applying a series of small incremental potential (x-axis) over counter electrode and working electrode. When anodic reaction and cathodic reaction reach an equilibrium, the current in the testing system would be the smallest value, and the potential at this point is noted as E_{corr} (open circuit potential or corrosion potential). The curve left to corrosion potential part is cathodic range, and right to it is anodic range. Tafel fit was conducted on the linear part of both cathodic and anodic range. Thus, two straight lines representing cathodic and anodic current should be carried out. The corresponding current to the intersection of these two straight lines is corrosion current (I_{corr}). The slope of anodic range (Tafel parameter of anode, $\boldsymbol{\beta}_{\mathrm{A}}$), together with corrosion potential and corrosion current, serve as three major indicators for corrosion resistance in Tafel test.

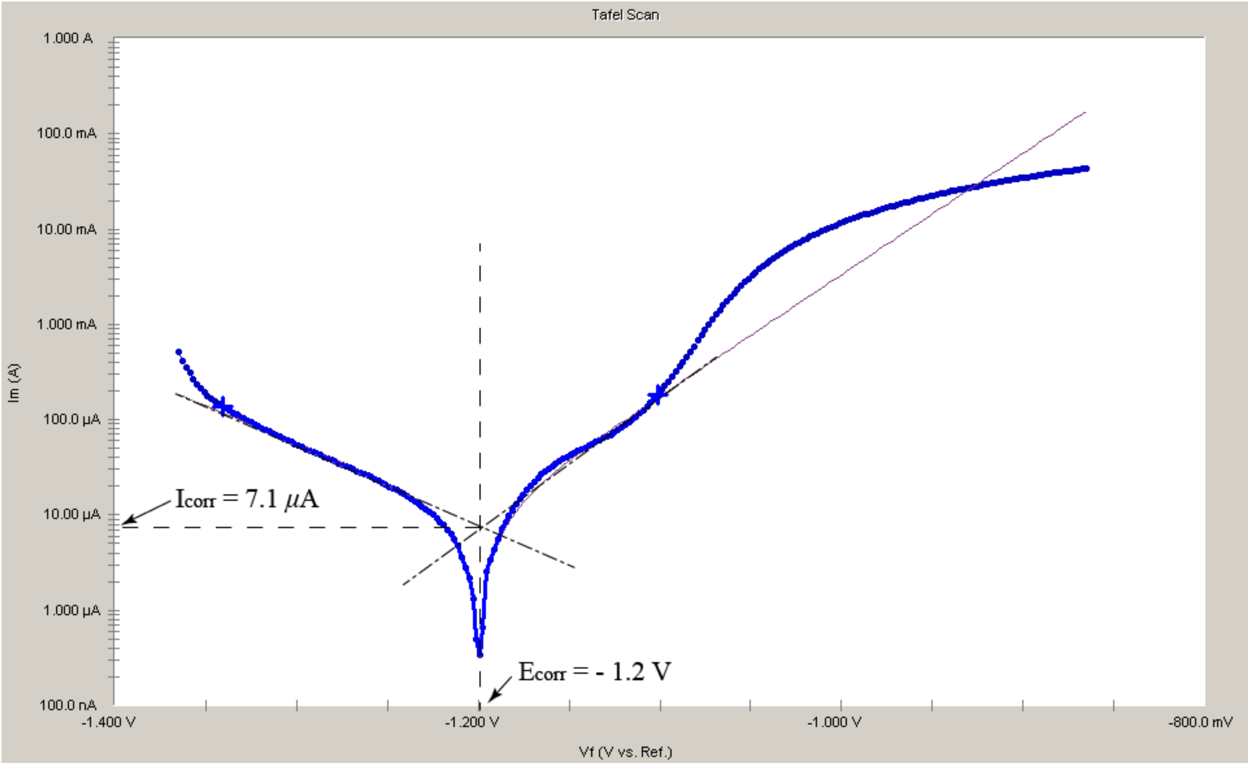

Figure 7. Tafel curve of tested sample.

By curve fitting on the linear part of both anode and cathode sides of the Tafel curve, the corrosion current could be calculated. With equation (2), corrosion rate could be assessed.

$$I_{\text{corr}} = \frac{\boldsymbol{\beta}_{\text{A}}\boldsymbol{\beta}_{\text{C}}}{2.303\boldsymbol{R}_{\text{P}}(\boldsymbol{\beta}_{\text{A}} + \boldsymbol{\beta}_{\text{C}})} \tag{1}$$

$$\text{Corrosion Rate} = \frac{KW_{\text{E}}I_{\text{corr}}}{AD} \tag{2}$$

Detailed notation and values used in the calculation is listed in Table 1. The corrosion rate obtained from the test is 0.595 mil/year, which is twice better than bare steel with corrosion rate higher than 1.0 mil/year.

Table 1 Parameters in equation (2) used for corrosion rate calculation

Notation	Value
I_{corr} / Corrosion Current in A	7.1 µA = 0.0000071 A
K / Unit Convert Constant	128800 (for mil/year)
W_{E} / Equivalent Weight in grams/equivalent	27.9225 (for iron -- 56 atom weight / 2 ions)
D / Density in g/cm^3	7.8
A / Sample area in cm^2	5.491

$$\text{Corrosion Rate} = \frac{KW_{\text{E}}I_{\text{corr}}}{AD} = \frac{128800 \times 27.9225 \times 0.0000071}{5.491 \times 7.8} = 0.595\ \text{mil/year}$$

Compared to previous reports, the cold sprayed Al-Zn coating has slightly higher corrosion rate than the arc wire sprayed Al-Zn coatings, which had a corrosion rate of 0.115 mil/year and 0.0993 mil/year (ten times better than bare steel), in corrosion resistance aspect. It is worth mentioning that no optimization were applied to operational process parameters of spraying process and the coating was deposited only based on experience of the operators. However, the quality and corrosion properties of cold sprayed Al-Zn coating can improve by optimization of spraying parameters in future.

(c) Description of Problems/Challenges

No problems observed in this quarter.

1- It seems that PIs need more time to obtain more data and evaluate the results in the best possible way. Since, this project will end in September 2018, PIs would like to request a "No cost extension" of the project until end of this year (December 31st, 2018). It was discussed on a phone call with Mr. Joshua Arnold (Program Director) and he verbally approved it but mentioned that we need to submit request with required explanation of the reason.

2- The PIs of this project, proposed to purchase a low cost cold spraying equipment to improve flexibility and mobility of the proposed concept. Since, thermal spraying technologies are mostly considered as stationary processes where samples required to be delivered to coating facility for deposition, availability of a mobile device that could deposit coatings on site is considered a great opportunity. However, it is a European technology with no North American developer yet. Unfortunately, DOT and PHMSA did not allow us to purchase this equipment since it is not made in USA.

(d) Planned Activities for the Next Quarter

The planned activities for next quarter are listed as below:

1) Sensor networking and corrosion damage characterization (Task 3.2);
2) Mechanical test on cold sprayed Al-Zn Samples (Task 3.2);
3) Risk assessment planning based on the corrosion detection (Task 3.3);
4) Full-size laboratory test preparation (Task 4.1).

(e) Reference

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